3. Transportation

by Thomas Maleck

Many of the questions relating to transportation can be answered by using the material found in the American Association of State Highway and Transportation Officials (AASHTO) book “A Policy on Geometric Design of Highways and Streets, 1984”. This guide is often referred to as the “GREEN BOOK”. Additional help can be found in Principles & Practice of Civil Engineering by Merle C. Potter.

3.1 Braking Distance (stopping sight distance)

Please refer to chapter three of the AASHTO's “A Policy on Geometric Design of Highways and Streets, 1984” to obtain the details needed to properly understand this material. See page 87 of the NCEES Reference Handbook, 3rd ed., for the equation used to calculate braking distance.

Example 3.1

A two lane highway has a grade of 2 percent. The design speed is 60 mph. Refer to the following table.

<table>
<thead>
<tr>
<th>Design Speed (mph)</th>
<th>Assumed Speed for Condition (mph)</th>
<th>Brake Reaction</th>
<th>Coefficient of Friction</th>
<th>Braking Distance on Level (\text{computed}^a) (ft)</th>
<th>Stopping Sight Distance Computed (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>44-50</td>
<td>2.5</td>
<td>0.30</td>
<td>215.1-277.8</td>
<td>376.4-461.1</td>
</tr>
<tr>
<td>55</td>
<td>48-55</td>
<td>2.5</td>
<td>0.30</td>
<td>256.0-336.1</td>
<td>432.0-537.8</td>
</tr>
<tr>
<td>60</td>
<td>52-60</td>
<td>2.5</td>
<td>0.29</td>
<td>310.8-413.8</td>
<td>501.5-633.8</td>
</tr>
<tr>
<td>65</td>
<td>55-65</td>
<td>2.5</td>
<td>0.29</td>
<td>347.7-486.6</td>
<td>549.4-724.0</td>
</tr>
<tr>
<td>70</td>
<td>58-70</td>
<td>2.5</td>
<td>0.28</td>
<td>400.6-583.3</td>
<td>613.1-840.0</td>
</tr>
</tbody>
</table>

\(^a\) Different values for the same speed result from using unequal coefficients of friction.

1. What is the assumed driver reaction time?
   (A) 1.0 sec
   (B) 1.5 sec
   (C) 2.0 sec
   (D) 2.5 sec
2. What is the lowest allowable assumed speed used for determining stopping sight distance?
   (A) 52 mph
   (B) 55 mph
   (C) 57 mph
   (D) 60 mph

3. What is the assumed coefficient of friction?
   (A) 0.28
   (B) 0.29
   (C) 0.30
   (D) 0.31

4. What is the expected braking distance?
   (A) 405 ft
   (B) 425 ft
   (C) 445 ft
   (D) 465 ft

5. How far does the vehicle travel before the vehicle decelerates?
   (A) 220 ft
   (B) 230 ft
   (C) 240 ft
   (D) 250 ft

6. What is the required stopping sight distance?
   (A) 625 ft
   (B) 665 ft
   (C) 695 ft
   (D) 715 ft

Solutions:
1. D From the table, brake reaction time equals driver reaction time, which equals 2.5 sec.
2. A From the table, assume speed for condition is 52-60 mph. For wet pavement 52 mph is assumed for design.
3. B From the table, coefficient of friction for a design speed of 60 mph is 0.29.
4. C \[ d = \frac{V^2}{2g(f \pm s)} \]
   \[ V = 60 \text{ mph, which } = 88 \text{ fps, } g = 32.2, f = 0.29, s = -0.02. \text{ s is negative because one direction of travel is going downhill.} \]
   Therefore, \( d = 445.36 \text{ ft.} \)
5. A Distance vehicle travels before braking is \( T \times V \) where
\[
T = 2.5 \text{ sec (driver reaction)}
\]
\[
V = 60 \text{ mph} = 88 \text{ fps}
\]
Therefore, distance = \( 2.5(88) = 220 \text{ ft.} \)

6. B Stopping sight distance = braking distance + distance the vehicle travels before braking, which equals questions No. 4 plus No. 5:
\[
445 + 220 = 665 \text{ ft}
\]

### 3.2 Sight Distance Over a Vertical Curve

The equations needed to solve the problem of sight distance over a vertical curve are found on page 87 of the NCEES Reference Handbook.

#### Example 3.2

A freeway has a 70 mph design speed. There is a 2% grade followed by a negative 3% grade. (Hint: this is a crest vertical curve.) Assume height of driver’s eye to be 3.5 ft and object height to be 0.5 ft. Refer to the table given in Example 3.1, as well as the following table.

<table>
<thead>
<tr>
<th>Design Speed (mph)</th>
<th>Premaneuver</th>
<th>Time(s)</th>
<th>Decision Sight Distance (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Detection &amp; Recognition</td>
<td>Decision &amp; Response Initiation</td>
<td>Maneuver (Lane Change)</td>
</tr>
<tr>
<td>30</td>
<td>1.5-3.0</td>
<td>4.2-6.5</td>
<td>4.5</td>
</tr>
<tr>
<td>40</td>
<td>1.5-3.0</td>
<td>4.2-6.5</td>
<td>4.5</td>
</tr>
<tr>
<td>50</td>
<td>1.5-3.0</td>
<td>4.2-6.5</td>
<td>4.5</td>
</tr>
<tr>
<td>60</td>
<td>2.0-3.0</td>
<td>4.7-7.0</td>
<td>4.5</td>
</tr>
<tr>
<td>70</td>
<td>2.0-3.0</td>
<td>4.7-7.0</td>
<td>4.0</td>
</tr>
</tbody>
</table>

1. What is the required length of vertical curve needed to satisfy design stopping sight distance?
   (A) 1435 ft
   (B) 2720 ft
   (C) 4550 ft
   (D) 1670 ft

2. What is the required length of vertical curve needed to satisfy the minimum value for decision sight distance?
   (A) 1435 ft
   (B) 2720 ft
   (C) 4550 ft
   (D) 1670 ft
Solutions:

1. B  From the table, stopping sight distance = 850 ft.

For a crest vertical curve:

\[ S < L \quad L = \frac{AS^2}{100(\sqrt{2H_1} + \sqrt{2H_2})^2} \]

\[ S > L \quad L = 2S - \frac{200(\sqrt{H_1} + \sqrt{H_2})^2}{A} \]

\[ L = \text{length of vertical curve} \]
\[ A = \text{algebraic difference in grade which equals } 2 - (-3) = 5 \]
\[ S = \text{sight distance requirement which equals 850 ft} \]
\[ H_1 = \text{height of driver's eye which equals 3.5 ft} \]
\[ H_2 = \text{height of object which equals 0.5 ft} \]

For \( S > L \)

\[ L = (2)(850) - \frac{(200)(\sqrt{3.5} + \sqrt{0.5})^2}{5} \]

\[ = 1434.17 \text{ ft} \]

False answer: \( S \) is not larger than \( L \).

For \( S < L \)

\[ L = \frac{(5)(850)^2}{(100)(\sqrt{7.0} + \sqrt{1})^2} \]

\[ = 2717.90 \text{ ft} \]

Correct answer: \( S \) is smaller than \( L \).

2. C  From the table, minimum value is 1,100 ft.

\( A, H_1 \) and \( H_2 \) do not change.

For \( S > L \)

\[ L = (2)(1100) - \frac{(200)(\sqrt{3.5} + \sqrt{0.5})^2}{5} \]

\[ = 1934.17 \text{ ft} \]

False answer: \( S \) is not larger than \( L \).

For \( S < L \)

\[ L = \frac{(5)(1100)^2}{(100)(\sqrt{7} + \sqrt{1})^2} \]

\[ = 4551.78 \text{ ft} \]

Correct answer: \( S \) is smaller than \( L \).
3.3 Sight Distance for a Sag Vertical Curve

The sag vertical curve equations are also found on page 87 of the NCEES Handbook.

Example 3.3

A highway has a 55 mph design speed. There is a negative 1 percent grade followed by a 2 percent grade. Refer to the following table.

<table>
<thead>
<tr>
<th>Assumed Speeds</th>
<th>Minimum Passing Sight Distance (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Design Speed (mph)</strong></td>
<td><strong>Passed Vehicle (mph)</strong></td>
</tr>
<tr>
<td>50</td>
<td>41</td>
</tr>
<tr>
<td>60</td>
<td>47</td>
</tr>
<tr>
<td>65</td>
<td>50</td>
</tr>
<tr>
<td>70</td>
<td>54</td>
</tr>
</tbody>
</table>

1. What is the required length of vertical curve needed to satisfy AASHTO stopping sight distance?
   (A) 320 ft
   (B) 585 ft
   (C) 200 ft
   (D) 1460 ft

2. What is the required length of vertical curve needed to satisfy AASHTO passing sight distance?
   (A) 320 ft
   (B) 585 ft
   (C) 200 ft
   (D) 1460 ft

3. What is the required length of vertical curve needed to satisfy AASHTO design sight distance?
   (A) 320 ft
   (B) 585 ft
   (C) 200 ft
   (D) 1460 ft

4. What is the required length of vertical curve to satisfy AASHTO requirements for comfort?
   (A) 320 ft
   (B) 585 ft
   (C) 200 ft
   (D) 1460 ft
Solutions:

1. A From the table in Example 3.1, stopping sight distance = 550 ft.
\[ A = (-1) - 2 = -3 \text{ or } 3 \]

For a sag vertical curve:
\[ S > L \quad L = 2S - \frac{400 + 3.55S}{A} \]
\[ S < L \quad L = \frac{AS^2}{400 + 3.55S} \]

For \( S > L \)

\[ L = 2(550) - \frac{400 + 3.55(550)}{3} \]
\[ = 315.83 \text{ ft} \]
Correct Answer: \( S \) is greater than \( L \).

For \( S < L \)

\[ L = \frac{3(550)^2}{400 + 3.55(550)} \]
\[ = 385.76 \text{ ft} \]
False answer: \( S \) is not less than \( L \).

2. D From the table given above, passing sight distance = 1950 ft for 55 mph.
\( A \) still equals 3.

For \( S > L \)

\[ L = 2(1950) - \frac{400 + 3.55(1950)}{3} \]
\[ = 1459.17 \text{ ft} \]
Correct answer: \( S \) is greater than \( L \).

For \( S < L \)

\[ L = \frac{3(1950)^2}{400 + 3.55(1950)} \]
\[ = 1557.9 \text{ ft} \]
False answer: \( S \) is not smaller than \( L \).

3. B From the table of Example 3.2, decision sight for 55 mph is 875 to 1150 ft.
Using a minimum value of 875 for this example. \( A \) still equals 3.

For \( S > L \)

\[ L = 2(875) - \frac{400 + 3.55(875)}{3} \]
\[ = 581.25 \text{ ft} \]
Correct answer: \( S \) is greater than \( L \).

For \( S < L \)

\[ L = \frac{3(875)^2}{400 + 3.55(1950)} \]
\[ = 313.67 \text{ ft} \]
False answer: \( S \) is not less than \( L \).
4. \[ L = \frac{AV^2}{46.5} \]

\[ A = 3 \text{ and } V = 55 \text{ mph.} \]

Therefore,

\[ L = \frac{3(55)^2}{46.5} \]

\[ = 195.16 \text{ ft} \]

### 3.4 Vertical Curve Elevations

Refer to page 96 of the NCEES Reference Handbook for a figure and equations used for calculations involving vertical curves.

#### Example 3.1

An 800 ft vertical curve with equal legs is provided for a highway crest vertical curve. The grade of the back tangent is 2% and the grade of the forward tangent is a negative 2%. The elevation of the Point of Vertical Intersection (PVI) is 1200 ft.

1. What is the elevation of the Point of Vertical Curve (PVC)?
   (A) 1192 ft
   (B) 1208 ft
   (C) 1184 ft
   (D) 1216 ft

2. What is the elevation of the Point of Vertical Tangent (PVT)?
   (A) 1192 ft
   (B) 1208 ft
   (C) 1184 ft
   (D) 1216 ft

3. What is the Rate of Change of Grade?
   (A) –0.050
   (B) –0.500
   (C) 0.01
   (D) 0.10

4. What is the Tangent Offset at the PVI?
   (A) –0.40
   (B) –2.00
   (C) –4.00
   (D) 0.20
5. If the PVI is at station 11+00 and the PVC is at station 7+00, what is the Tangent Offset at station 8+00?
   (A) 0.25
   (B) 0.50
   (C) 1.00
   (D) −0.25

6. What is the Curve Elevation at station 8+00?
   (A) 1193.75 ft
   (B) 1194.00 ft
   (C) 1194.50 ft
   (D) 1195.00 ft

Solutions:

1. A \[ PVC = PVI - (g_1)L/2 \]
   \[ = 1200 - (2)8/2 = 1192 \]
   \( L \) is in stations

2. A \[ PVT = PVI + (g_2)L/2 \]
   \[ = 1200 + (-2)8/2 = 1192 \]

3. B Rate of Change:
   \[ r = \frac{g_2 - g_1}{L} = \frac{(-2) - 2}{8} \]
   \[ = -0.500 \]

4. C \[ a = \text{Parabola Constant} \]
   \[ a = \frac{g_2 - g_1}{2L} = \frac{(-2) - 2}{2(8)} \]
   \[ = -0.25 \]

   \( E = \text{Tangent Offset at PVI} \)
   \[ E = a \left( \frac{L}{2} \right)^2 = (-0.25) \frac{8^2}{2^2} \]
   \[ = -4.00 \]

5. D \[ y = \text{Tangent Offset} \]
   \[ y = ax^2 = (-0.25)(1)^2 \]
   \[ = -0.25 \]
   \( (x \text{ is in stations}) \)

6. A \[ \text{Curve Elevation} = Y_{PVC} + g_1x + ax^2 \]
   \[ Y_{PVC} = 1192 \text{ ft} \]
   \[ g_1 = 2\% \]
\[ x = 1 \text{ station} \\
\[ a = -0.25 \\
Therefore: Curve Elevation at station 8+00 equals: \\
1192 + 2(1) - 0.25(1)^2 = 1193.75 \\

3.5 Horizontal Curves

The horizontal curve figure and equations are found on page 97 of the NCEES Handbook.

Example 3.5

A horizontal curve with a 1000 ft radius is to be provided for two perpendicular roads. The station of the PI is 12+400.00.

1. What is the Intersection of Angle?
   (A) 90°
   (B) 120°
   (C) 45°
   (D) 60°

2. What is the Degree of Curve?
   (A) 5.73°
   (B) 5.00°
   (C) 4.25°
   (D) 6.81°

3. What is the Tangent Distance?
   (A) 800 ft
   (B) 550 ft
   (C) 1000 ft
   (D) 1100 ft

4. What is the External Distance?
   (A) 411.8 ft
   (B) 414.2 ft
   (C) 618.2 ft
   (D) 411.2 ft

5. What is the Length of the Middle Ordinate?
   (A) 292 ft
   (B) 293 ft
   (C) 288 ft
   (D) 283 ft
6. What is the Length of Curve?
(A) 1200.00 ft
(B) 1242.81 ft
(C) 1500.00 ft
(D) 1570.80 ft

7. What is the stationing of the PC?
(A) 17+70.80
(B) 15+81.00
(C) 2+00.00
(D) 2+70.80

8. What is the stationing of the PT?
(A) 17+70.80
(B) 15+81.00
(C) 2+00.00
(D) 2+70.80

Solutions:

1. A Since the roads are perpendicular, the Angle of Intersection is 90°.

2. A The Degree of Curve \( = \frac{5729.58}{R} \)

\[ R = 1000 \text{ ft. Therefore,} \]

\[ D = \frac{5729.58}{1000} = 5.73° \]

3. C The Tangent Distance is

\[ T = R \tan(I/2) \]

\[ I = 90° \text{ (from question 1). Therefore,} \]

\[ T = (1000)\tan(90/2) = 1000.00 \text{ ft} \]

4. B The External Distance is

\[ E = R\left[\sec(I/2) - 1\right] \]

\[ = 1000[1.41421 - 1] = 414.21 \text{ ft} \]

5. B The length of the Middle Ordinate is

\[ M = R - R \cos \frac{I}{2} \]

\[ R = 1000.00 \]

\[ I = 90° \]

Therefore: \( M = 292.89 \text{ ft} \)

6. D The Length of Curve is
\[ L = \frac{100I}{D} \]
\[ = \frac{100(90)}{5.72958} = 1570.80 \text{ ft} \]

7. C Station of PC = station of PI – Tangent Distance:
\[ PC = 12+00.00 - 1000.00 = 2+00.00 \]

8. A Station of PT equals station of PC plus Length of Curve:
\[ PT = PC + L \]
\[ = 2 + 00.00 + 1570.80 \]
\[ = 17 + 70.80 \]

### 3.6 Superelevations

To calculate the superelevation of a highway, refer to the material on page 88 of the NCEES Handbook, 3rd ed. The superelevation equation for railroads is also presented there.

#### Example 3.6

For the horizontal curve in Example 3.5, what is the minimum superelevation needed to provide for a 50 mph design speed? Refer to the following table.

<table>
<thead>
<tr>
<th>Design Speed (mph)</th>
<th>Maximum $e$</th>
<th>Maximum $f$</th>
<th>Total $(e + f)$</th>
<th>Maximum Degree of Curve</th>
<th>Rounded Maximum Degree of Curve</th>
<th>Minimum Radius (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>.08</td>
<td>.17</td>
<td>.25</td>
<td>53.54</td>
<td>53.5</td>
<td>107</td>
</tr>
<tr>
<td>30</td>
<td>.08</td>
<td>.16</td>
<td>.24</td>
<td>22.84</td>
<td>22.75</td>
<td>252</td>
</tr>
<tr>
<td>40</td>
<td>.08</td>
<td>.15</td>
<td>.23</td>
<td>12.31</td>
<td>12.25</td>
<td>468</td>
</tr>
<tr>
<td>50</td>
<td>.08</td>
<td>.14</td>
<td>.22</td>
<td>7.54</td>
<td>7.5</td>
<td>764</td>
</tr>
<tr>
<td>60</td>
<td>.08</td>
<td>.12</td>
<td>.20</td>
<td>4.76</td>
<td>4.75</td>
<td>1,206</td>
</tr>
<tr>
<td>65</td>
<td>.08</td>
<td>.11</td>
<td>.19</td>
<td>3.86</td>
<td>3.75</td>
<td>1,528</td>
</tr>
<tr>
<td>70</td>
<td>.08</td>
<td>.10</td>
<td>.18</td>
<td>3.15</td>
<td>3.0</td>
<td>1,910</td>
</tr>
</tbody>
</table>

**NOTE:** In recognition of safety considerations, use of $e_{\text{max}} = 0.04$ should be limited to urban conditions.

(A) 0.165
(B) 0.04
(C) 0.140
(D) 0.027

**Solution:**

The maximum allowable lateral friction force is required to minimize the needed superelevation. Therefore, from the given table, the maximum allowable friction factor $f$ is 0.140.

The required superelevation $e$ is equal to
\[ e + f = \frac{V^2}{gR} \]

Therefore:

\[ e = \frac{V^2}{gR} - f \]

\[ V = 50 \text{ mph} = 73.33 \text{ ft/sec} \]
\[ R = 1000 \text{ ft} \]
\[ g = 32.2 \text{ ft/sec}^2 \]

\[ e = \frac{73.33^2}{32.2(1000)} - 0.14 = 0.027 \]

The answer is D.

### 3.7 Spirals

Spirals for highways are analyzed using the equation given on page 88 of the NCEES Reference Handbook. Railroad spirals are also analyzed using the equation given there.

**Example 3.7**

For the horizontal curve in Examples 3.5 and 3.6, what is the recommended length of spiral transition?

- (A) 150 ft
- (B) 200 ft
- (C) 250 ft
- (D) 300 ft

**Solution:**

The length of spiral is equal to:

\[ L_s = 1.6 \frac{V^3}{R} \]

\[ V = 50 \text{ mph} \]
\[ R = 1000 \text{ ft} \]

\[ L_s = 1.6 \frac{50^3}{1000} = 200 \text{ ft} \]

The answer is B.
4. Airport Design

by Francis McKelvey

The questions relating to airport layout and design can be answered by referring to pages 94 and 95 of the NCEE Handbook, 3rd ed. We will present several of the more common problems encountered when designing an airport.

Example 4.1

The preliminary vertical profile for a transport airport runway centerline is given below. The specifications for the geometric design of the vertical profile of the centerline of a runway are presented on p. 95 of the Handbook.

![Vertical Profile Diagram]

1. The minimum required length of a vertical curve at the point of intersection A is most nearly:
   (A) 300 ft
   (B) 600 ft
   (C) 1300 ft
   (D) 2000 ft

2. The minimum required length of a vertical curve at the point of intersection B is most nearly:
   (A) 100 ft
   (B) 500 ft
   (C) 1000 ft
   (D) 1500 ft

3. The minimum required length of a vertical curve at the point of intersection C is most nearly:
   (A) 200 ft
   (B) 500 ft
   (C) 700 ft
   (D) 1200 ft
4. The minimum required distance between point of intersection A and point of intersection B is most nearly:
   (A) 1000 ft
   (B) 1300 ft
   (C) 2000 ft
   (D) 2300 ft

5. The minimum required distance between point of intersection B and point of intersection C is most nearly:
   (A) 500 ft
   (B) 700 ft
   (C) 2200 ft
   (D) 2500 ft

Solutions:

1. C  p.95 - Transport Airports: \[ L_1 = 1.30(1000) = 1300 \text{ ft} \]

2. C  p.95 - Transport Airports: \[ L_2 = 1.00(1000) = 1000 \text{ ft} \]

3. D  p.95 - Transport Airports: \[ L_3 = 1.20(1000) = 1200 \text{ ft} \]

4. D  p.95 - Transport Airports: \[ D = 1000(A + B) \]
   \[ = 1000(1.30 + 1.00) = 2300 \text{ ft} \]

5. C  p.95 - Transport Airports: \[ D = 1000(B + C) \]
   \[ = 1000(1.00 + 1.20) = 2200 \text{ ft} \]
Example 4.2

The preliminary vertical profile for an utility airport runway centerline is given. The specifications for the geometric design of the vertical profile of the centerline of a runway are given on Page 95.

1. The minimum required length of a vertical curve at the point of intersection $A$ is most nearly:
   (A) 150 ft
   (B) 300 ft
   (C) 450 ft
   (D) 600 ft

2. The minimum required length of a vertical curve at the point of intersection $B$ is most nearly:
   (A) 100 ft
   (B) 200 ft
   (C) 300 ft
   (D) 600 ft

3. The minimum required distance between point of intersection $A$ and point of intersection $B$ is most nearly:
   (A) 150 ft
   (B) 200 ft
   (C) 675 ft
   (D) 875 ft

4. The maximum gradient of the runway centerline between point of intersection $A$ and point of intersection $B$ is most nearly:
   (A) 0.00%
   (B) +0.50%
   (C) +1.00%
   (D) +1.50%
Solutions:

1. **C**  
   - Utility Airport: \( L_1 = 300(1.50) = 450 \text{ ft} \)
   - \(-1.50\% \quad 0.00\% \)
     
     \[ A \quad 1.50\% \]

2. **D**  
   - Utility Airports: \( L_2 = 300(2.00) = 600 \text{ ft} \)
   - \(0.00\% \quad 2.00\% \)
     
     \[ B \quad -2.00\% \]

3. **D**  
   - Utility Airports: \( D = 250(A + B) \)
     
     \[ = 250(1.50 + 2.00) = 875 \text{ ft} \]
     
     \[ A \quad 1.50\% \quad 2.00\% \quad B \]

4. **A**  
   - From p.95 the maximum gradient = 2.00%. But also the maximum grade change = 2.00%.
   
   \( A + A: \)
     
     \[ -1.50\% \quad X \quad 1.50\% + X \]
     
     \[ 1.50 + X \leq 2.00. \quad \therefore X = 0.5\% \]

   \( A + B: \)
     
     \[ X \quad 2.00\% + X \quad -2.00\% \]
     
     \[ X + 2.00 \leq 2.00. \quad \therefore X = 0.00\% \]
Example 4.3

The historical pattern of wind at an airport location has been plotted in a windrose given below. The wind speeds plotted are in the ranges between 0-4, 4-15, 15-31 and 31-47 miles per hour. The airport runway is to be designed for aircraft weighing more than 12,500 pounds. The specifications for wind analysis are given on Page 94 of the NCEES Handbook.

1. The optimal runway orientation at this airport is most nearly:
   (A) N-S
   (B) NW-SE
   (C) E-W
   (D) NE-SW

2. The percentage of time a runway in the N-S direction may be used by aircraft weighing more than 12,500 pounds at this airport without exceeding crosswind specifications is most nearly:
   (A) 67%
   (B) 81%
   (C) 87%
   (D) 95%

3. The percentage of time the winds come from the NW and have a wind speed of between 4 and 15 miles per hour is:
   (A) 1%
   (B) 9%
   (C) 13%
   (D) 21%
4. The percentage of time a runway in the E-W direction may be used by aircraft taking off and landing toward the East without exceeding cross-wind specifications is most nearly:
   (A) 28%
   (B) 40%
   (C) 56%
   (D) 68%

Solutions:
1. **C** Based on wind data given on the next four pages, the runway orientation and percent uses are:
   - N-S: 81%
   - NW-SE: 77%
   - E-W: 86%
   - NE-SW: 77%

   Therefore, E-W maximized wind coverage.

1. **Continued** — Runway in N-S direction —

   p.94 infers the maximum cross wind to be 15 mph.

   \[
   \% = \frac{12+18+1+3+10+7+6+9+5+5+2+2}{12+18+1+3+1+10+7+6+9+5+5+2+2} = 81\%
   \]

   The N-S runway may be used 81% of the time with cross winds less than 15 mph.
1. Continued — Runway in the NW-SE direction —

p.94 infers the maximum cross wind to be 15 mph.
\[ \% = 12+18+1+3+1+10+7+6+9+2.5+2.5+2.5 = 77\% \]
The NW-SE runway may be used 77% of the time with cross winds less than 15 mph.

1. Continued — Runway in E-W direction —

p.94 infers the maximum cross wind to be 15 mph.
\[ \% = 12+18+1+3+1+10+7+6+9+5+5+4 = 86\% \]
The E-W runway may be used 86% of the time with cross winds less than 15 mph.
1. Continued — Runway in NE-SW direction:

p.94 infers the maximum cross wind to be 15 mph.

\[ \% = 12 + 18 + 1 + 3 + 1 + 10 + 7 + 6 + 9 + 2.5 + 2.5 + 2.5 + 2.5 = 77\% \]

The NE-SW runway may be used 77% of the time with cross winds less than 15 mph.

2. B For a runway in the N-S direction:

\[ \% = 12 + 18 + 1 + 3 + 1 + 10 + 7 + 6 + 9 + 5 + 5 + 2 + 2 = 81\% \]

The N-S runway may be used 81% of the time with cross winds less than 15 mph.
3. B The shaded area represents the percentage of time the wind comes from the NW and is between 4 and 15 mph. Therefore, 9% of the time.

4. B The shaded area represents the percentage of time a runway may be used in an East direction so that cross winds are less than 15 mph:
\[ \% = 12 + 9 + 1 + 3 + 1 + 5 + 5 + 4 = 40\% \] of the time.
5. Pavement Design

by Gilbert Baladi

Problems involving pavement design can be worked referring to the equations and table on page 95 of the NCEES Handbook, 3rd ed. The following examples illustrate the solution technique.

Example 5.1

A coal fired power plant is served by 25 trucks. When loaded, each truck consists of one single-axle of 14,000 pounds (the front axle), two tandem-axles of 32,000 pounds each (the middle axles), and one single-axle of 22,000 pounds (the back axle). Each truck makes 25 daily trips. The weights on the same axles when the truck is empty and leaving the power plant are 10,000, 12,000, and 8,000. A two-lane road is to be designed to serve the power plant and to last for a period of 10 years.

1. What is the load equivalency factor for a 14,000-pound single-axle?
   (A) 0.027
   (B) 0.36
   (C) 0.189
   (D) 1.0

2. What is the load equivalency factor for a 32,000-pound tandem-axle?
   (A) 8.88
   (B) 6.97
   (C) 0.36
   (D) 0.857

3. What is the design ESAL for the incoming traffic?
   (A) 9,704,438
   (B) 388,176
   (C) 970,444
   (D) 26,588

4. What is the design ESAL for the outgoing traffic?
   (A) 344,012
   (B) 943
   (C) 34,402
   (D) 1,376
Solutions:

1. B From the table on page 95, the load equivalency factor for a 14,000-pound single-axle load is 0.36.

2. D From the table on page 95, the load equivalency factor for a 32,000-pound tandem-axle load is 0.857.

3. A To calculate the design ESAL for the incoming traffic, first calculate the ESAL per truck. This implies that the load equivalency factor (LEF) for each axle on the truck must be obtained:

   For the 14,000-pound single-axle, LEF = 0.36.
   For the 32,000-pound tandem-axle, LEF = 0.857.
   For the 220,000-pound single-axle, LEF = 2.18.

   The total ESAL per truck = 1(0.36) + 2(0.857) + 1(2.18) = 4.254 ESAL/truck.

   For 25 trucks, with each truck making 25 trips per day, the total ESAL per day is
   \[ 25(25)(4.254) = 2658.75 \text{ ESAL/day} \]

   For a 10-year design life, the total design ESAL is
   \[ 10(365)(2658.75) = 9,704,438 \text{ ESAL} \]

4. A To calculate the design ESAL for the outgoing traffic, follow the same steps as in the solution to question 3, except use the axle weights of the empty truck:

   For the 10,000-pound single-axle, LEF = 0.0877.
   For the 12,000-pound tandem-axle, LEF = 0.0144.
   For the 8,000-pound single-axle, LEF = 0.0343.

   The total ESAL per truck = 1(0.0877) + 2(0.0144) + 1(0.0343) = 0.1508 ESAL/truck.

   For 25 trucks, with each truck making 25 trips per day, the total ESAL per day is
   \[ 25(25)(0.1508) = 94.25 \text{ ESAL/day} \]

   For a 10-year design life, the total design ESAL is
   \[ 10(365)(94.25) = 344,013 \text{ ESAL} \]

Example 5.2

For the power plant of Example 5.1, the design structural number for the incoming traffic (loaded trucks) is 5.2 and for the outgoing traffic (empty trucks) is 3.0. The design engineer used the following material for road construction:

A 12-inch-thick sand sub-base with a layer coefficient of 0.10
A 6-inch-gravel base with a layer coefficient of 0.13
An asphalt-concrete surface layer with a layer coefficient of 0.40
1. What is the required asphalt-concrete thickness for the incoming traffic (loaded trucks)?
   (A) 8 in.
   (B) 6 in.
   (C) 10 in.
   (D) 4 in.

2. What is the required asphalt-concrete thickness for the outgoing traffic (empty truck)?
   (A) 3 in.
   (B) 3.6 in.
   (C) 2.6 in.
   (D) 4 in.

3. For the material data given above, what is the required gravel thickness that will produce the same structural number as a one-inch-thick asphalt-concrete layer?
   (A) 3.1 in.
   (B) 0.33 in.
   (C) 6 in.
   (D) 1 in.

Solutions:

1. **A** Use the equation on page 95:
   \[ SN = a_1D_1 + a_2D_2 + a_3D_3 \]
   Solving for the thickness of the asphalt-concrete yields
   \[ D_1 = \frac{SN - a_2D_2 - a_3D_3}{a_1} \]
   Therefore,
   \[ D_1 = \frac{5.2 - 0.1(12) - 0.13(6)}{A} = 8 \text{ in.} \]

2. **C** Solving for \( D_1 \) by following the same steps as in the solution to Question 1 yields
   \[ D_1 = \frac{3.0 - 0.1(12) - 0.13(6)}{A} = 2.6 \text{ in.} \]

3. **A** The structural number \( SN \) of a one-inch asphalt-concrete layer is \( 1(0.4) = 0.4 \).
   The required thickness \( D_2 \) of the gravel that will yield a structural number of 0.4 can be calculated from the following equation:
   \[ SN_2 = a_2D_2 \]
   Solving for \( D_2 \) gives
   \[ D_2 = \frac{SN_2}{a_2} = \frac{0.4}{0.13} = 3.1 \text{ in.} \]
Example 5.3

Two single-axle trucks travel one road in one direction twice each day. The first truck consists of a 10,000-pound front single-axle and an 18,000-pound rear single-axle. The second truck consists of a 12,000-pound front single-axle and a 24,000-pound rear single-axle. Assume that, for each trip, the first truck delivers a unit of damage to the road.

1. For each trip, how many units of damage are delivered to the road by the second truck?
   (A) 3.22
   (B) 2.96
   (C) 1.09
   (D) 0.54

2. For each day, how many units of damage are delivered to the road by the second truck?
   (A) 6.44
   (B) 2.18
   (C) 4.62
   (D) 5.92

Solutions:

1. **B** The relative damage delivered by each truck is proportional to the ESAL of each truck. Thus, the ESAL of each truck must be calculated first.

   **Truck 1:**
   
   The LEF for a 10,000-pound single-axle = 0.0877
   The LEF for an 18,000-pound single-axle = 1.0
   The total ESAL of truck 1 = 1.0 + 0.0877 = 1.0877

   **Truck 2:**
   
   The LEF for a 12,000-pound single-axle = 0.189
   The LEF for a 24,000-pound single-axle = 3.03
   The total ESAL of truck 2 = 3.03 + 0.189 = 3.219

   The number of units of damage delivered to the pavement by truck 2 are
   
   $3.219 / 1.0877 = 2.96$

2. **D** The second truck makes two trips per day. The number of units of damage are

   $2(2.96) = 5.92$
The required structural number $SN$ of an asphalt pavement to protect the roadbed soil is 3.5. The required structural number to protect the sub-base material is 2.84. The required structural number to protect the base material is 2.0. The pavement is constructed of the following materials:

- Sand sub-base with a layer coefficient of 0.11.
- Gravel base with a layer coefficient of 0.14.
- Asphalt-concrete surface with a layer coefficient of 0.4.

1. What is the required thickness of the asphalt-concrete layer?
   (A) 6.0 in.
   (B) 5.0 in.
   (C) 4.0 in.
   (D) 3.0 in.

2. What is the required thickness of the base layer?
   (A) 6.0 in.
   (B) 5.0 in.
   (C) 4.0 in.
   (D) 3.0 in.

3. What is the required thickness of the sub-base layer?
   (A) 6.0 in.
   (B) 5.0 in.
   (C) 4.0 in.
   (D) 3.0 in.

**Solutions:**

1. B The AASHTO structural number $SN$ equation is given as
   \[ SN = a_1D_1 + a_2D_2 + a_3D_3 \]
   where the $a_i$ and $D_i$ are the layer coefficient and layer thickness. The above equation can be rewritten as follows:
   \[ SN = SN_1 + SN_2 + SN_3 \]
   where $SN$ is the structural number of the pavement, and $SN_i$ is the $SN$ of layer $i$. Since the required $SN$ to protect the base material is 2.0, it is inferred that the $SN$ of the asphalt-concrete is 2.0. Therefore:
   \[ SN_1 = a_1D_1 = 2.0 \]
   We solve for $D_1$:
   \[ D_1 = SN_1/a_1 = 2.0 / 0.4 = 5 \text{ in.} \]

2. A Given that the required structural number to protect the sub-base is 2.84, we have
\[ SN = a_1D_1 + a_2D_2 = 2.84 \]

Since \( a_1 = 0.4 \), \( D_1 = 5 \text{ in.} \), and \( a_2 = 0.14 \), we solve for \( D_2 \) as follows:

\[ D_2 = \frac{SN - a_1D_1}{a_2} \]

Therefore,

\[ D_2 = \frac{2.84 - 0.4 \times 5}{0.14} = 6 \text{ in.} \]

3. A The required thickness of the sub-base layer can be obtained by solving the following structural number equation:

\[ SN = a_1D_1 + a_2D_2 + a_3D_3 \]

All variables are known except the thickness \( D_3 \) of the sub-base. Solving for \( D_3 \):

\[ D_3 = \frac{SN - a_1D_1 - a_2D_2}{a_3} \]

Therefore,

\[ D_3 = \frac{3.5 - 0.4 \times 5 - 0.14 \times 6}{0.11} = 6 \text{ in.} \]
42. If the wall is made of concrete with a unit weight of 150 lb/ft$^3$, what is the factor of safety against sliding? Take the factor of safety as the ratio of the resisting forces to the driving forces.
   (A) 2.00  
   (B) 1.05  
   (C) 0.95  
   (D) 3.69

Questions 43 – 44

A 2-directional 24-foot wide asphalt concrete (AC) surfaced road is to be constructed along with a total of 12-foot asphalt concrete shoulders. The road and shoulders cross section includes 12-inch granular subbase, 6-inch gravel base, and 6-inch asphalt concrete. The asphalt paver places the AC in two courses: 4-inch base course and 2-inch surface course. The paver places the AC in 12-ft wide strips at an average speed of 2 miles per day.

43. If the density of the placed and compacted AC is 145 pcf, then the total weight in pounds of the AC material (both surface and base courses) in a one-square-yard surface area is about:
   (A) 752.5  
   (B) 652.5  
   (C) 600.0  
   (D) 700.0

44. The density of the AC material in the trucks is 120 pcf. The daily volume (the number of cubic yards) of the AC surface course in the delivery trucks is about:
   (A) 1045  
   (B) 1245  
   (C) 945  
   (D) 2145

45. The new road was designed and constructed to carry the 20-year design period of traffic. The projected two-directional traffic in terms of 18,000 pounds equivalent single axle load (ESAL) over the 20-year design period was 2,900,000 ESAL. The design ESAL (the number of ESAL used in the design of the road) is about:
   (A) 2,900,000  
   (B) 1,450,000  
   (C) 5,800,000  
   (D) None of the above
A freeway in a rural area has the following design criteria:

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<th>Description</th>
<th>Value</th>
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<tr>
<td>Design Speed</td>
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<tr>
<td>Wet Coefficient of Friction</td>
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<tr>
<td>Perception of Reaction Time</td>
<td>2.5 secs</td>
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<tr>
<td>Height of Eye</td>
<td>3.5 ft</td>
</tr>
<tr>
<td>Height of Object</td>
<td>0.5 ft</td>
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<tr>
<td>Top of Vehicle</td>
<td>4.25 ft</td>
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</tbody>
</table>

46. The distance traveled by a vehicle during the perception and reaction of the driver before stopping is most nearly:
   (A) 260 ft
   (B) 290 ft
   (C) 320 ft
   (D) 350 ft

47. The distance traveled by the vehicle while decelerating to a stop (leaving skid marks) is most nearly:
   (A) 500 ft
   (B) 550 ft
   (C) 580 ft
   (D) 620 ft

48. If the maximum allowable superelevation and lateral friction force are 0.08 and 0.10, respectively, the minimum design radius is most nearly:
   (A) 1745 ft
   (B) 1815 ft
   (C) 1910 ft
   (D) 1975 ft
## Answers to the Civil Examination

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<th>Hydraulics/ Hydrology</th>
<th>Transportation</th>
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<td>20. A</td>
<td>44. C</td>
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<td>4. B</td>
<td>22. D</td>
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<tr>
<td>5. A</td>
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